Polarization-Independent Self-Collimated Beam Splitting in Two-Dimensional Photonic Crystals

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Abstract- Polarization-independent splitting of self-collimated transverse-electric and transverse-magnetic polarized waves in a two-dimensional square photonic crystal are demonstrated. The beam splitting is facilitated by the existence of sharp edges in flat equifrequency contours.

I. INTRODUCTION

Photonic crystals (PC) are dielectric materials, whose refractive index is periodically modulated in space. They have been attracted a great deal of attention since they are able to manipulate light at the wavelength scale.

The beam splitter is one of the most crucial photonic components in which beam splitting in and outside the PC structure could be achieved by several methods, such as using line-defect PC waveguides [1], coupled-cavity PC waveguides [2] and directional coupling [3]. Beam splitters based on self-collimation effect, originating from complex dispersion of light in the PC have also been proposed [4]. The idea of using a directional band gap to split self collimated beams with large angular separation was suggested by Matthews et al [5] and experimentally demonstrated on the transverse-electric (TE) polarized beam [6].

In this work, polarization independent wide angular splitting of a self collimated beam inside a square PC is demonstrated and the influence of source width is discussed.

II. RESULTS and DISCUSSION

Two-dimensional (2D) PC is composed of alumina rods of radius r=1.55 mm and relative dielectric constant of 10.0 in a square lattice in air with a lattice constant of 3.5 mm. The Plane Wave Expansion (PWE) method, as implemented in the BandSOLVE software by RSoft Design Group is utilized to obtain the band structure (BS) and the equifrequency contours (EFC) for the infinite PC structure.

To show the self-collimation effect and the wave splitting, the EFCs of the transverse-magnetic (TM, electric field parallel to rods) and transverse-electric (magnetic field parallel to rods) modes are calculated for the 2^{nd} and 3^{rd} bands of the PC, as shown in Fig.1(a) and (b), respectively. The two bands overlap significantly for the TM case, whereas overlapping is negligible for the TE polarization. Besides, the slices (EFCs) at 27.2 GHz reveal that the contours are almost flat normal to the ΓX direction and own sharp corners along the ΓM direction. Thus, a wave of either the TE or the TM polarization incident at small angles along the ΓM direction is self-collimated within the PC with the refraction angle close to ±45°. However, a real source possesses finite transverse extent corresponding to a spread along the normal to the propagation direction in the reciprocal space, as suggested by the black dashed construction lines in Fig. 1(c) and (d). In this case, even if the wave is incident normally, a range of spatial modes are excited within the PC, most of which are self-collimated along the same direction, as demonstrated by the arrows in Fig. 1(c) and (d). Hence, a normally-incident beam of finite transverse extent is

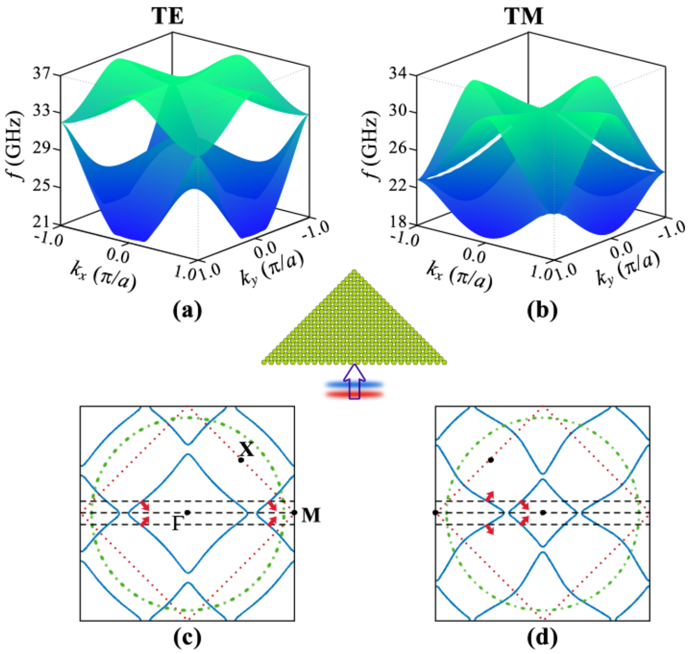

Fig.1-Band plots for the second and third TE **(a)** and TM **(b)** bands, accompanied by the corresponding EFCs at 27.2 GHz **(c)** and **(d)**, respectively. The inset depicts the beam splitter on which the waves are incident along the ΓM direction. The red-dotted squares and the green-dash-dotted circles in (c) and (d) represent the first BZ and the EFC at 27.2 GHz in air, respectively. The black-dashed horizontal lines and arrows in (c) and (d) represent the construction lines corresponding to source width in reciprocal space and the propagation directions of the beams splitting inside the PC, respectively.

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expected to split across the air-PC interface along the ΓM direction around 27.2 GHz, irrespective of its polarization, although the PC geometry is not disturbed by line defects, etc.

The EFCs for 27.2 GHz in Fig. 1(c) and (d) have two components centered on the Γ and M points. Thus, each construction line in Fig. 1(c) and (d) intersects the EFCs at two distinct points, resulting in further splitting of each beam to obtain more complicated devices, such as 1x4 splitters. However, the directions of velocity vectors in each splitting beam for both polarization in Fig. 1(c) and Fig. 1(d) are so close that differentiation of the further splitting of the beams becomes difficult, as in Fig. 2.

The propagation of the TE and TM-polarized waves in the 2D PC structure is simulated through the 2D Finite-Difference Time-Domain (FDTD) method, where the computational domain is surrounded by a perfectly matched layer absorbing boundary, as implemented in the FullWAVE software. The structure, on which the beams are incident along the ΓM direction, is visualized in the inset of Fig. 1. The output face of the PC is truncated normal to the ΓX direction so that a right isosceles triangular geometry is obtained and the waves inside the PC arrive at the PC-air interface normally, to minimize the reflection losses. The PC is excited by a plane wave at 27.2 GHz, whose transverse profile is Gaussian and the transverse width is varied between $2a$ and $10a$. The FDTD results are presented in Fig. 2.

As the source width increases, part of the EFCs remaining between the construction lines in Fig.1(c) and (d) becomes curved. Direction of the velocity vectors therefore deviates more and eventually, the beam width increases. Although this effect is evident in Fig. 2 for both polarizations it is much clear for the TE polarization in Fig. 2(a).

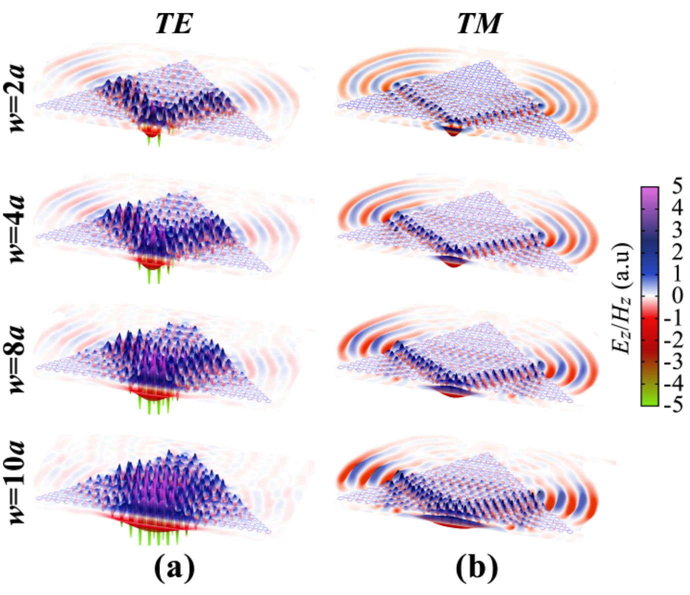

Fig. 2- FDTD simulations for the propagation of the beams at 27.2 GHz with TE **(a)** and TM **(b)** polarizations in 2D PC. The source width increases from $2a$ to $10a$ from top to down.

Polarization independent self collimated beam splitting could be achieved more efficiently in annular photonic crystals since they offer more flexibility to match the EFCs for the TE and TM polarizations in PC [7].

III. CONCLUSION

A 2D PC with high filling ratio of dielectric scatters in air is demonstrated to facilitate 50-50% splitting of incident beams with finite width at a specific frequency range upon refraction across the air-PC interface, irrespective of the source polarization.

TE and TM-polarized waves are split at close angles, while the transmitted beam width within the PC is higher in TE case. The splitting ability of TE waves is deteriorated as the source width is increased, whereas it is preserved for TM waves.

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REFERENCES

[1] P. Pottier, S. Mastroiacovo, and R. M. De La Rue, "Power and polarization beam-splitters, mirrors, and integrated interferometers based on air-hole photonic crystals and lateral large index-contrast waveguides", *Opt. Exp.*, Vol.14, pp.5617-5633, 2006.
[2] M. Bayindir, B. Temelkuran, and E. Ozbay, "Photonic-crystal-based beam splitters", *Appl. Phys. Lett.*, Vol.77, pp.3902-3904, 2000.
[3] I. Park, H.-S. Lee, H.-J. Kim, K.-M. Moon, S.-G. Lee, B.-H. O, S.-G. Park, and E.-H. Lee, "Photonic crystal power-splitter based on directional coupling", *Opt Exp.*, Vol. 12, pp.3599-3604, 2004.
[4] X. F. Yu and S. H. Fan, "Bends and splitters for self collimated beams in photonic crystals", *Appl. Phys. Lett.*, Vol. 83, pp. 3251-3253, 2003.
[5] A. F. Matthews, S. K. Morrison, Y. S. Kivshar, "Self-collimation and beam splitting in low-index photonic crystals", *Opt. Comm.*,Vol. 279, pp. 313-319, 2007.
[6] A. F. Matthews, "Experimental demonstration of self-collimation beaming and splitting in photonic crystals at microwave frequencies", *Opt. Comm.*, Vol. 282, pp. 1789-1792, 2009.
[7] A. Cicek and B. Ulug, "Polarization-independent waveguiding with annular photonic crystals", *Opt. Exp.*, Vol. 17, pp.18381-18386, 2009